Searching for “Stealthy” Supersymmetry at the LHC with the CMS Experiment

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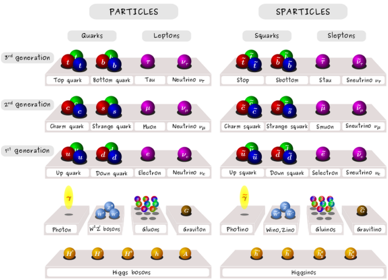
Supersymmetry, A Review

By introducing a **supersymmetry** to the SM...

- Each SM particle gets a **supersymmetric partner.**
- **“Unnaturalness” of Higgs mass corrections can be eliminated!**
- **R-parity** is introduced to **avoid rapid proton decay.**
- The **lightest neutralino** would be a natural **dark matter candidate.**

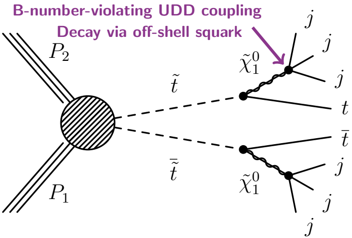


“Classic” signatures of this SUSY have not been observed...

- **Lightest neutralinos** from SUSY particle decays would be “seen” as significant missing transverse energy in detector.
- **Is other phenomenology possible—could SUSY be “stealthy” and not manifest as obviously?**

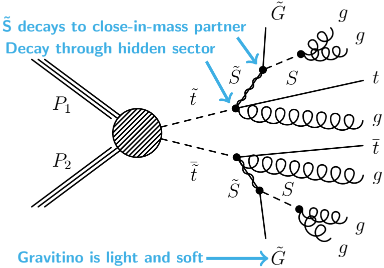
R-parity Violating SUSY

- Allow for interaction terms that **do not conserve baryon or lepton number.**
- As a consequence, **the LSP is no longer stable and decays to SM.**
- Top squarks produced at colliders **would not result in large measured E_T^{miss}.**



Stealth (SYY) SUSY

- Let there be also a **hidden sector** which simply **contains a sfermion and a scalar partner.**
    - Soft SUSY-breaking is suppressed in hidden sector.
    - SUSY is approximately conserved and the sfermion and scalar are very close in mass.
- In this case, **the top squark** decays through this **hidden sector.**



We focus on these (largely unexplored) **low-E_T^{miss} signatures of $\tilde{t}$ decays.**

Strategy for RPV/Stealth SUSY Search

Considering final state of $t\bar{t}$ + jets with no E_T^{miss}...

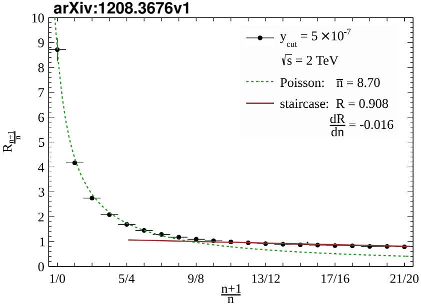
- The **primary topology feature** of the signal is **high jet multiplicity**.
- Requiring **one lepton** helps reduce QCD background.
- We would like to **use/fit the N_J spectrum**; but, jet multiplicity is hard to model at high N_J, so we **rely on data**.

From theory, the ratio of number of events **N_{J+1}/N_J** can be described by **two components.**

We design a fit function thats describes this N_J distribution to avoid statistical fluctuations in the tail

$$f(x) = a_2 + \left[\frac{(a_1 - a_2)^x}{(a_0 - a_2)^{x-2}}\right]^{\frac{1}{2}}$$

where $x = N_J - 7$, $a_0 = \frac{N_8}{N_7}$, $a_1 = \frac{N_{10}}{N_9}$, $a_2 = \lim_{x\to\infty} \frac{N(x+1)}{N(x)}$



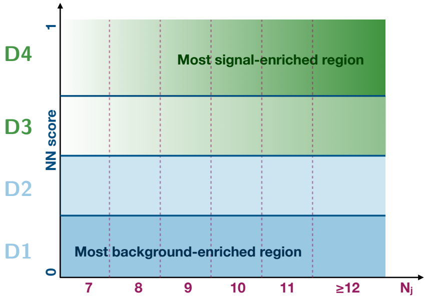
Strategy for RPV/Stealth SUSY Search

We train a neural network (NN) to discriminate signal vs background, which is **uncorrelated with N_J**.

Events are divided into **four NN score regions** where the **background N_J shape is the same in each region**.

A simultaneous fit of N_J in the four NN score regions is then performed.

Events at high N_J in D4 are more signal-like, whereas **events at low N_J in D1 are more background-like.**



Which Events to Consider?

Many jets in final state!

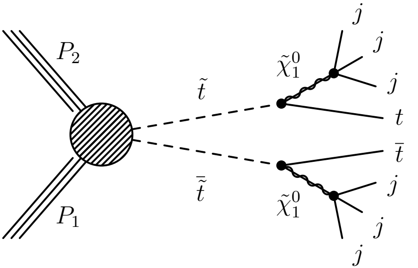
- Require at least 7 jets
- $H_{\mathrm{T}} > 300$ GeV

There are tops and reduce QCD!

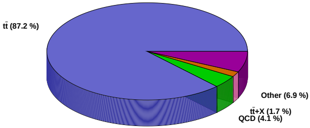
- At least one b jet
- Exactly one lepton
- $50 < M_{\mathrm{b},\ell} < 250$ GeV, **loose leptonic top tag**

Removes most background while maintaining good signal efficiency.

R-parity Violating Signature



2016 MC Composition

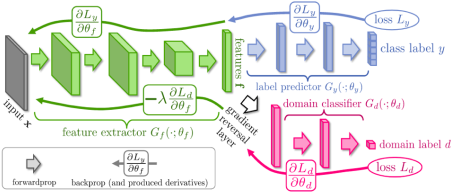


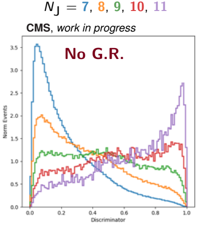
We train a neural network to enhance the discrimination between signal and background.

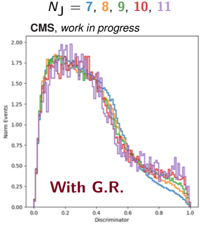
Inputs to the NN (done in center-of-mass frame):

- 4-vectors of 7 highest momentum jets
- 4-vector of lepton
- Jet energy-momentum tensor eigenvalues and Fox-Wolfram moments

It is a simple connected network **using gradient reversal to remove dependence on N_J.**







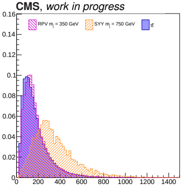
Training is done with **$t\bar{t}$ as the background component** and **all signal models/masses as the signal component.**

Neural Network Input Variables Sampler (2016)

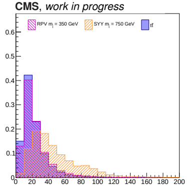
“Low-level” Variables

Jet 4-vectors (highest momentum jet)

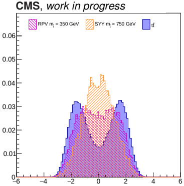
Leading Jet p_T [GeV]



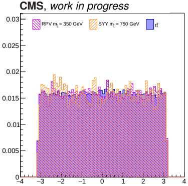
Leading Jet mass [GeV]



Leading Jet η



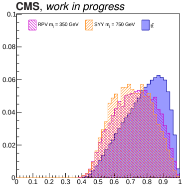
Leading Jet ϕ



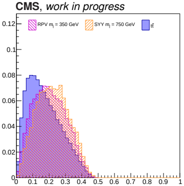
“High-level” Variables

Jet Momentum Tensor Eigenvalues

Eigenvalue 0

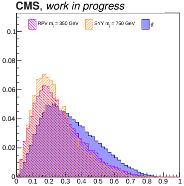


Eigenvalue 1

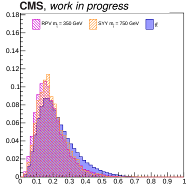


Fox-Wolfram Moments

2nd Moment

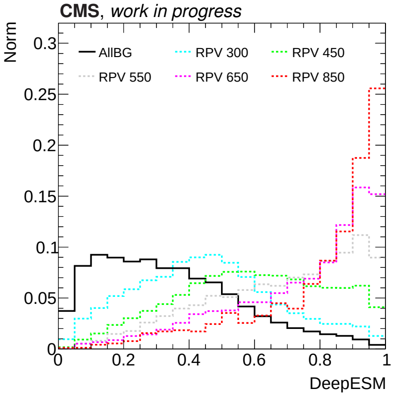


4th Moment

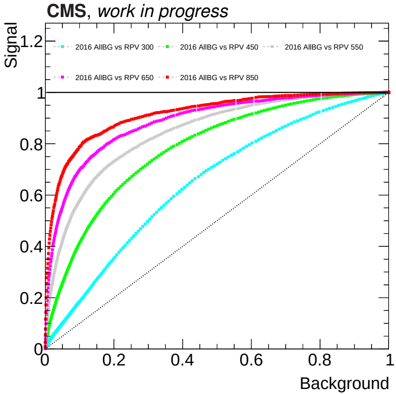


Neural Network Performance (2016)

Neural Network Output Score



ROC Curve



Good discrimination with **best performance for highest mass models.**

Training on individual mass models gives no significant improvement.

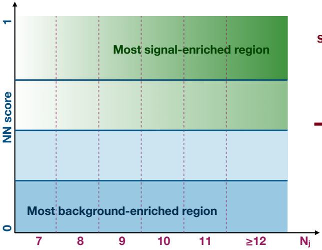
Binning by Neural Network Score

Create **four bins** in the **NN output score**.

- "D1" is background-dominated and acts as a proxy control region
- "D4" has much higher signal sensitivity

Important Considerations

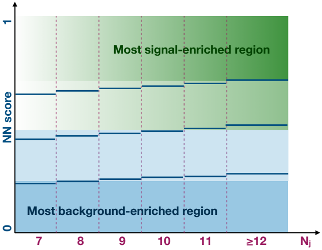
1. Background estimation relies on having the **same N_J shape in each NN bin**.
2. However, some **residual N_J dependence remains after using NN**.
3. Thus, the edges of the four NN bins are adjusted on a per-N_J level to achieve **equal background fraction in each bin and the N_J shape stays the same.**



Use metric correlated with significance to determine fractions.

D4: 2.4%, D3: 6.5%, D2: 38.9%, D1: 47.8%

Smoothly adjust NN bin edges.



Fit Procedure

Simultaneous binned fit to the N_J shape—6 bins starting at $N_\mathrm{J} = 7$ and the **last bin being $\mathbf{N_J \geq 12}$**—in each of the four NN discriminant bins.

Signal strength, r, is the parameter of interest.

Fit Components:

- **$\mathrm{t\bar{t}}$** parameterized shape $\rightarrow$ **same for all NN bins.**
- **QCD** estimate from control region.
- **TTX ($\mathrm{t\bar{t}}$ + X)** backgrounds MC histograms.
- **Other** backgrounds **(diboson, triboson, etc.)** MC histograms.
- Signal MC histograms.

Robusty Estimating QCD Contribution

QCD background at high N_J has **low MC event counts** and **large event weights**.

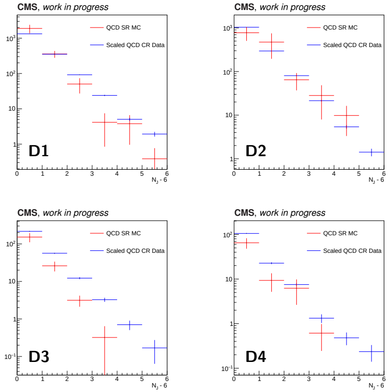
This could **wash out $\mathbf{N_J}$ shape differences** coming from signal! So a **QCD**-dominated control region in data is used.

Require non-isolated muon with $\mathbf{p_T > 55}$ GeV in baseline selection.

Define transfer factor:

$$TF = \left.\frac{N(SR)}{N(CR)}\right|_{\mathrm{MC}}$$

Used to normalize the **QCD** estimate in **data** in the control region.



Important Systematics ($t\bar{t}$)

For **$\mathbf{t\bar{t}}$** it is important to take into account anything that would **change the $\mathbf{N_J}$ shape asymmetrically between NN bins.**

Systematic uncertainty is derived as a ratio:

$$\left.\frac{N_{\mathrm{J}}(\text{in bin D}i)}{N_{\mathrm{J}}(\text{for all bins})}\right|_{\text{Syst.}}$$

"Vanilla" Variations:

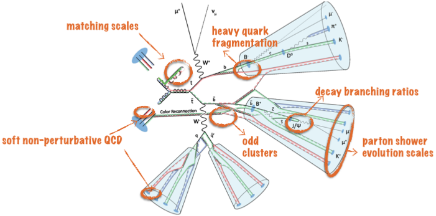
- Most related to SFs and reweighting, e.g. b tag SF uncertainty, lepton ID, etc. Also JEC/JER.

From Control Region

- How the NN-N_{J} correlation is modeled by MC.

Analysis-Specific & Physics Modeling:

- Color reconnection, ME-PS matching scale, underlying event
- Initial-state and final-state radiation
- Jet mass & p_{T} spectrum



Total Fit in Simulation

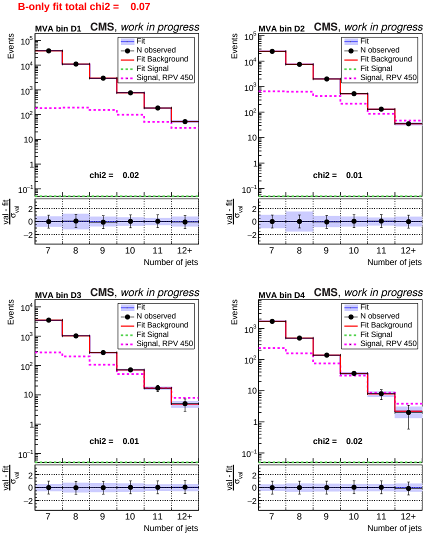
Bottom ratio are the **fit pulls**
$\Rightarrow (N_{\text{obs}} - \text{fit})/\sqrt{N_{\text{obs}}}$

Shaded bands
$\Rightarrow (\text{fit uncertainty})/\sqrt{N_{\text{obs}}}$

RPV 450 signal shape shown as a reference.

Quality of **the fit** is good and the background model works well.

Background-only fit to 2016 MC

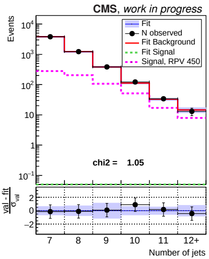


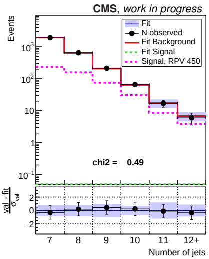
Signal Injection Test

Inject RPV signal ($m_{\tilde{t}} = 450$ GeV) at nominal cross-section: the fit should now want to include **a signal component.**

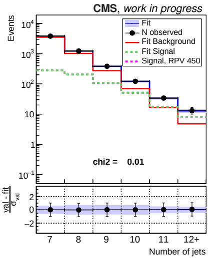
2016

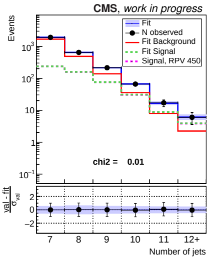
Background-only Fit





Signal+Background Fit





With **background-only fit** we observe some **non-zero pulls**

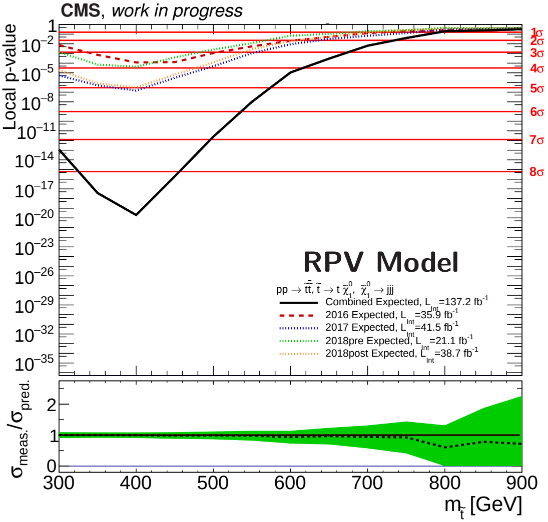
Here to obtain **best fit**, **a signal component** is added and the pulls are much closer to 0.

Expected Signal Sensitivity

Pseudo data + injection of RPV signal at nominal cross-section.

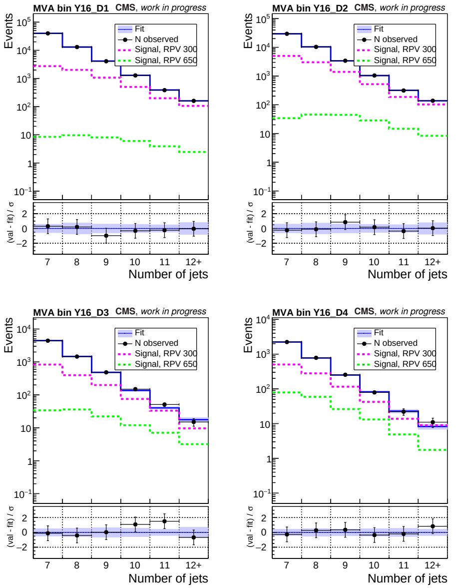
Peak sensitivity is at a **top squark mass of 400 GeV.**

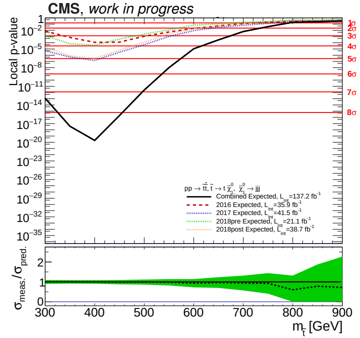
Over range of mass points and within uncertainty, **the fit finds the signal strength that was injected**.

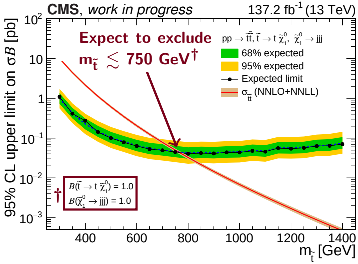


Expected Results for the RPV Model

Background-only Fit for 2016







Concluding Remarks

- Expanding SM to include **supersymmetry** restores “naturalness” in model.
- Traditional collider searches for **SUSY** have not found anything**—perhaps SUSY is “stealthier” than we thought.**
- Our analysis is one of the first of its kind to search for RPV and Stealth SUSY
  - Using CMS’s full Run2 data set, we expect model exclusion power up to $m_{\tilde{t}} \simeq 750$ GeV.
  - **We are motivated to perform 0-lepton and 2-lepton versions of this search!**

BACKUP

Datasets, Objects, and Triggers

Datasets: SingleElectron and SingleMuon

Objects

Selection	Jets	Electrons	Muons
Quality	AK4 PFJets with CHS DeepCSV medium WP for b jets	Tight cut-based ID Mini-isolation < 0.1	Medium ID Mini-isolation < 0.2
$\lvert\eta\rvert$	< 2.4		
p_T	> 30 GeV	2016: > 30 GeV 2017/2018: > 37 GeV	> 30 GeV

Triggers

Year	Electron Triggers	Muon Triggers
2016	HLT_Ele27_WPTight_Gsf HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Photon175	HLT_IsoMu24 HLT_IsoTkMu24 HLT_Mu50 HLT_TkMu50
2017	HLT_Ele35_WPTight HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Photon200	HLT_IsoMu24 HLT_IsoMu27 HLT_Mu50
2018	HLT_Ele35_WPTight HLT_Ele115_CaloIdVT_GsfTrkIdT HLT_Photon200	HLT_IsoMu24 HLT_IsoMu27 HLT_Mu50

General Systematics

Non-$t\bar{t}$, non-**QCD** multijet backgrounds are included as **TTX ($t\bar{t}$ + V)** and **Other**. Systematics for these are straightforward to input to Combine as up/down histograms.

Sources included as nuisance parameters are:

- Luminosity uncertainty: 2.5% for 2016, 2.3% for 2017 and 2.5% for 2018.
- JEC and JER recommended uncertainties.
- b-tagging efficiency SF uncertainty
- Lepton ID, isolation, trigger SF uncertainties.
- H_{T} correction SF uncertainties
- Pileup reweighting uncertainties
- PDF (signal) uncertainties
- Cross-section uncertainties (30%)

PDF uncertainties for signal partially cover for ISR uncertainty as SUS uncertainties cannot be used.

Systematics Summary

Source	ttbar	non-ttbar	signal
Luminosity	-	2.5	2.5
Jet energy scale	0–4 (18)	5–21 (100)	1–11 (31)
Jet energy resolution	0–2 (10)	1–15 (100)	0–6 (14)
b tagging	0–1 (3)	0–2 (12)	0–2 (2)
Parton distribution function	0–1 (2)	0–1 (8)	0–2 (7)
Pileup reweighting	0–2 (7)	0–7 (28)	0–2 (4)
ECAL trigger inefficiency	0–1 (1)	0–1 (2)	0–1 (2)
Factorization/renormalization scale	0–2 (5)	1–8 (18)	0–3 (4)
Lepton id/iso/trigger efficiency	0–1 (1)	3–5 (5)	3–4 (4)
Nominal shape difference	0–4 (27)	-	-
S_{NN}-N_J modeling (from CR)	0–12 (37)	-	-
Jet mass & p_T modeling	0–4 (15)	-	-
H_T (extrapolated vs. derived SF ($N_J = 8$))	0–1 (4)	0–6 (10)	-
H_T (constant SF at high H_T)	0–2 (9)	-	-
H_T (SF from $N_J = 7$)	0–7 (27)	-	-
H_T (SF zeroed)	0–5 (17)	-	-
Initial-state radiation	0–4 (15)	-	-
Final-state radiation	0–8 (27)	-	-
ME-PS matching scale	0–14 (82)	-	-
Color reconnection model	0–10 (44)	-	-
Underlying event tuning	0–7 (100)	-	-